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Lamont Geological Observatory

Technical Reports on Seismology

No. 7

Studies of Frontal, Cyclonic and Hurricane Microseisms Generated in the Western North Atlantic

Introductory and Part 1 - Frontal Microseisms

Lamont Geological Observatory

(Columbia University)

Palisades, New York

STUDIES OF FRONTAL, CYCLONIC AND HURRICANE MICROSEISMS GENERATED IN THE WESTERN NORTH ATLANTIC

INTRODUCTORY AND PART I - FRONTAL MICROSEISMS

Technical Report No. 7

by

William L. Donn William L. Donn

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October 1950

ABSTRACT

Following a discussion of the methods of sampling and measurement of microseism storms, a series of case histories of microseism storms of frontal origin and related marine weather conditions are given. Seismograms from the Columbia University New York City station in 1948, and the Palisades, N.Y. station in 1949 and 1950 together with records from Weston Observatory have been utilized in this study. Based on the case histories presented conclusions are drawn regarding period, amplitude, regularity and origin of frontal microseisms. Possible meteorological applications are indicated.

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INTRODUCTORY AND PART - I FRONTAL MICROSEISMS

CONTENTS

* Parts II and III are to be published separately.

INTRODUCTION

This report is based on a study of microseisms generated by meteorological fronts and storms in the western North Atlantic Ocean and the adjacent Caribbean Sea and Gulf of Mexico. Most of the microseism storms resulting from fronts and extra-tropical cyclones (referred to as "cyclones" in all of this report) occurring during the half year intervals from August to January of 1948 and 1949 were included in the study. All of the microseism storms generated by tropical cyclones (referred to as "hurricanes" here) during 1948, 1949 and 1950, in addition to some from other years, were also studied. In the case of each of the above types of meteorological disturbances seismograms from a large number of stations (listed later) were utilized.

The purpose of the investigation was severalfold: (1) to supply further basic data bearing on the problem of the mechanism of origin and propagation of microseisms; (2) to note relations between meteorological conditions and microseisms; (3) to note possible influences of geologic structure on the transmission of microseisms, and the existence of unknown or doubtful structures that might be revealed through transmission anomalies.

The study and the presentation has been arranged in three major parts in order to show best the meteorological and related microseismic conditions. As embodied in the title, above, these parts relate microseisms to fronts, cyclones, and hurricanes, and are referred to respectively as "frontal microseisms", "cyclonic microseisms" and "hurricane microseisms". Each of these parts will be submitted for publication separately.

No historical synopsis of the problem is given here since the history and much of the current thought concerning microseisms are so fully presented by Ramirez (1) and Gilmore (2). A complete abstracted microseism bibliography as of October 1949 is given by Gutenberg (3).

ACKNOWLEDGEMENTS

Professor Maurice Ewing of Columbia University was the sponsor of the research program and extended invaluable advice during the research and manuscript preparation. Necessary funds were supplied from Contract W-28-099 ac-396 between Columbia University and the United States Air Force.

A number of people were of great assistance in their co-operation through furnishing seismograms covering many long intervals. Marion H. Gilmore, Geophysicist at the United States Navy Hurricane Weather Central, Miami, Florida supplied records of the Navy Hurricane Tracking Seismograph Stations in and around the Gulf of Mexico and Caribbean Sea. Father Daniel Linehan, S.J. and Mr. V. John Mankiewicz made available a six months continuity of records from the Weston College observatory. Seismograms and other information were generously furnished by Father J. Joseph Lynch, S.J. and Dr. William Lynch of Fordham University. The United States Coast Geodetic Survey, and in particular Dr. Leonard Murphy, were very helpful in supplying records from the seismograph stations on Bermuda and San Juan, P.R. Copies of records from the Azores were transmitted by Prof. A. Ferrieca at Largo de Santa Isabel.

In addition to the seismograms, marine weather charts were essential for the study. The chief source of this weather data has been the Ocean Forecast Section of the United States Weather Bureau, at La Guardia Field on Long Island. They have supplied continuously for several years, four of each of the six-hourly North Atlantic synoptic surface charts. Mr. W. D. Boehner, Officer-in-Charge has been especially cooperative. Supplementary weather data necessary in critical instances was also obtained in many cases from the Air Weather Service at Andrews Air Force Base in Washington, D.C. and from the WBAN Analysis Center at the U.S. Weather Bureau, also in Washington, D.C.

Assistance, particularly in the performance of measurements on the seismograms was given by Alan Vestrich, Maurice Rosen, and Robert Katz, all senior students in geology and physics at Brooklyn College.

PROCEDURE OF STUDY

A. SAMPLING AND MEASUREMENT OF SEISMOGRAMS

The treatment of the data used here is given at some length, especially since the literature is fairly barren of techniques employed by other researchers.

The methods actually used for measuring, recording and plotting information on the seismograms were modified from time to time during the study. The goal was to obtain an accurate picture of microseism storms together with preceding and following background conditions. In particular the times of beginning and ending of such storms, together with the value and time of maximum intensity were desired. Consequently, the simplest sampling technique that would give a good picture of these values was wanted.

Further, a major problem in the seismogram study, particularly in the early part of the work, has been just what to measure. This is especially troublesome when amplitudes of storm microseisms and background are close, or when amplitudes and periods of the wave trains are irregular, as a result of either generating or instrumental conditions. Unfortunately some selection was therefore necessary in measuring amplitudes and periods. In general only undeformed waves or trains were studied. Also, as amplitudes diminished, those waves were examined which appeared to be of the same form and period as the preceding more distinct storm microseisms. This was important in particular when a newer, closer meteorological storm followed in the path of an earlier receding one. The following two sections summarize the methods employed in study of amplitudes and periods.

Amplitudes - In all cases of amplitude study, measurements were made by estimating to tenths of a millimeter, the double amplitude or upper to lower peak distances. The line thickness was then subtracted to give more correct values. Hereafter the term "amplitude" will refer to "double amplitude", a quantity determinable more readily and accurately.

1. The first procedure consisted of measuring all waves of amplitude distinctly above the background for the five minutes preceding each half hour. These values were averaged and plotted against time.

2. A second procedure was to measure the single maximum wave in each minute for five minutes preceding each half hour,

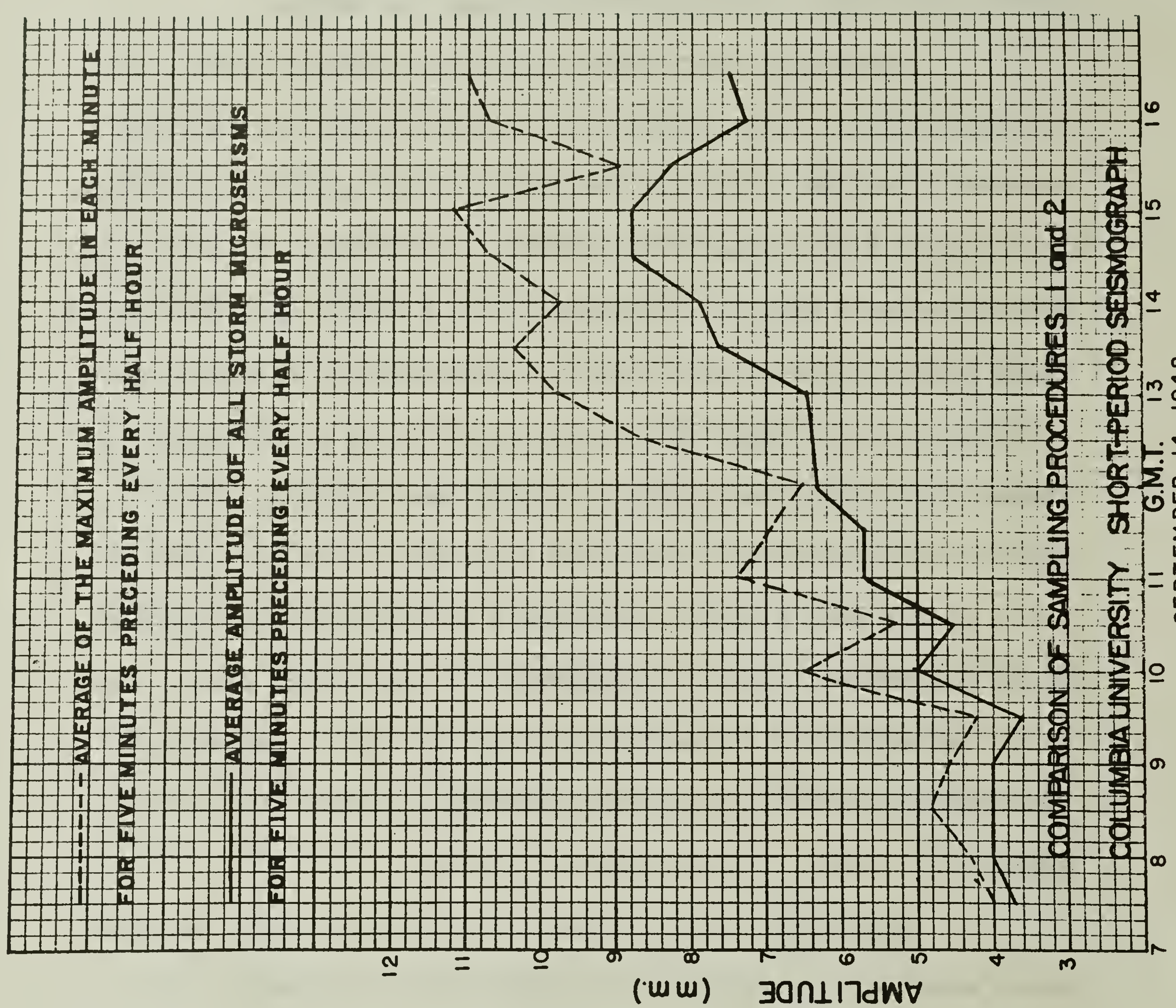
AVERAGE OF THE MAXIMUM AMPLITUDE IN EACH MINUTE
FOR FIVE MINUTES PRECEDING EVERY HALF HOUR
AVERAGE AMPLITUDE OF ALL STORM MICROSEISMS
FOR FIVE MINUTES PRECEDING EVERY HALF HOUR
COMPARISON OF SAMPLING PROCEDURES 1 and 2
COLUMBIA UNIVERSITY SHORT-PERIOD SEISMOGRAPH
G.M.T.
SEPTEMBER 14, 1948
7
8
9
10
11
13
14
15
16
AMPLITUDE (m.m.)
3
4
5
6
7
8
9
10
11
12

Figure 1

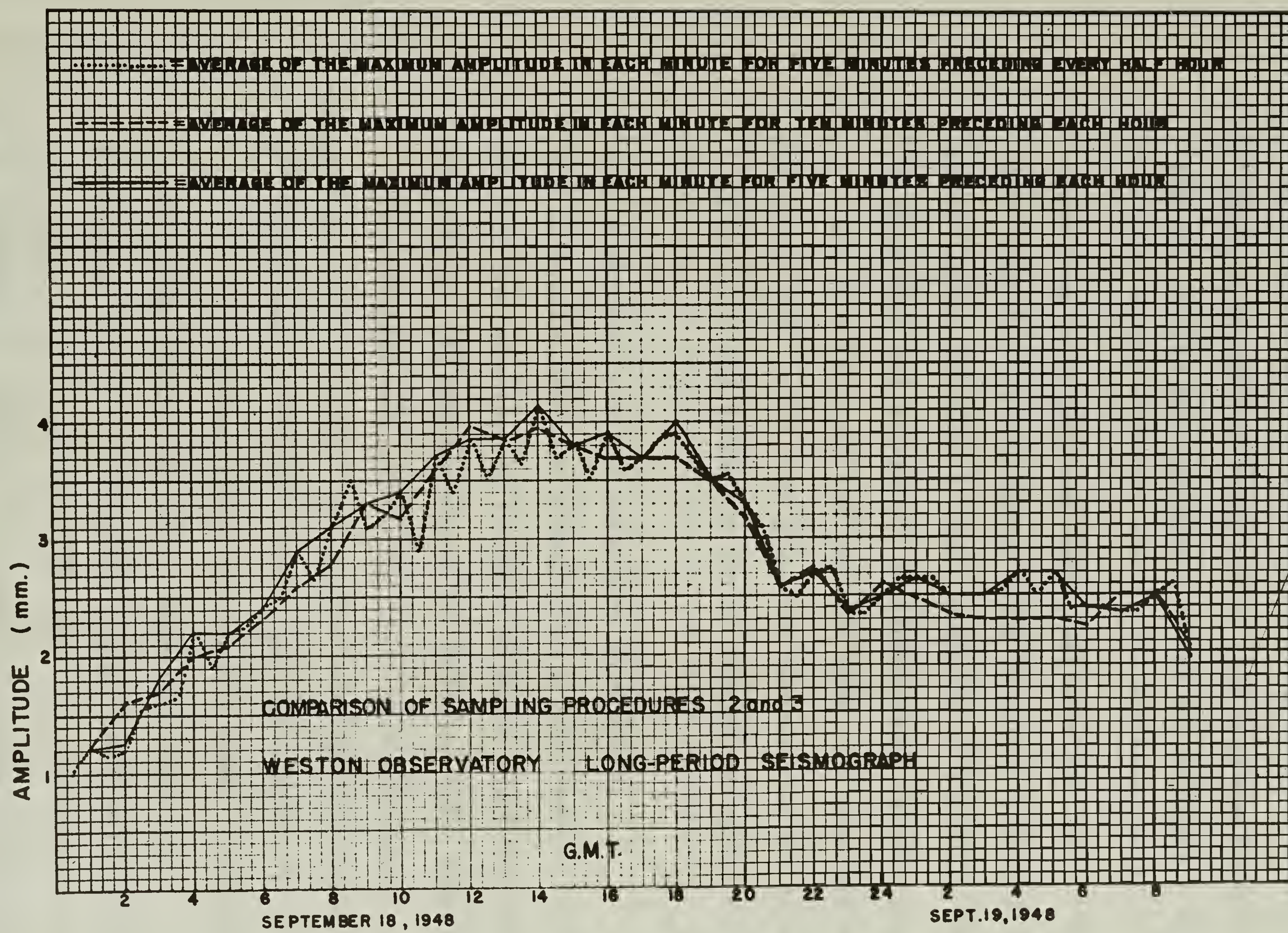
AVERAGE OF THE MAXIMUM AMPLITUDE IN EACH MINUTE FOR FIVE MINUTES PRECEDING EVERY HALF HOUR
AVERAGE OF THE MAXIMUM AMPLITUDE IN EACH MINUTE FOR TEN MINUTES PRECEDING EACH HOUR
AVERAGE OF THE MAXIMUM AMPLITUDE IN EACH MINUTE FOR FIVE MINUTES PRECEDING EACH HOUR
COMPARISON OF SAMPLING PROCEDURES 2 and 3
WESTON OBSERVATORY LONG-PERIOD SEISMOGRAPH
AMPLITUDE (mm.)
1
2
3
4
G.M.T.
2 4 6 8 10 12 14 16 18 20 22 24 2 4 6 8
SEPTEMBER 18, 1948
SEPT. 19, 1948

Figure 2

with the average of these five values plotted against time. This method was used only on the first few storms studied. Figure 1 compares the curves resulting from methods one and two.

3. The relatively fine sampling above gave amplitude intensity curves of great irregularity, with fine variations difficult to interpret, and of doubtful value. Consequently average measurements of the maxima for five minutes preceding each hour were plotted, and compared with the averages for ten minutes preceding each hour. The curves for a storm using the methods in two and three are compared in Figure 2.

4. As the work progressed and more records accumulated, it seemed that a sufficiently accurate picture of the microseisms storm could be obtained by measuring and plotting amplitudes after sampling the single maximum per minute, for five minutes preceding every two hours. For intervals of particular interest, the sampling was narrowed to hourly measurements. To obtain less significant background conditions, the sampling was spread to four-hourly measurements.

The amplitude -time curves are rarely smooth, the irregularities often being a result of one or two anomalously high or low wave peaks. The peaks may have been a result of instrumental response, or conditions involved in generation and propagation.

Periods - The measurement of periods is more difficult owing to their lesser variation and the compression of time on the seismograms. Much greater selection is necessary here in order to choose symmetrical and undeformed waves for accurate time measurements. In general, with microseisms from only one storm prevailing, the wave trains of maximum amplitude were observed first, but these often lacked the necessary symmetry. Once definite storm microseisms appeared it was necessary to select those wave trains which seemed to be of storm origin, disregarding background, although often of comparable or greater amplitude. When apparent, a distinction was also made between microseism periods from close and distant meteorological storms.

The actual sampling corresponded closely to the methods used in amplitude study. Five wave trains were selected and the averages of the component waves were plotted for the same time intervals. In this selection it was often necessary to examine the record for an interval of 30 minutes around the hour in question. Frequently, period studies could not commence as early nor continue as late as amplitude observations owing to the irregularity of smaller waves. Periods were sampled at either two or four hour intervals depending on the variation.

In measuring periods, distances along the time axis of the records were estimated to tenths of a millimeter, with little error being expected in such measurements owing to the magnified proportional parts scale used. These distances were then converted into seconds so that the time error depended on the ratio of distance to time on the different records, which in turn depended on drum speeds. The errors are summarized in the table below which also summarizes the sources of seismic data used for measurements.

Instrument	Accuracy of Period Measurements
Columbia University	
New York City (1948)	0.15 sec.
Palisades, N.Y. (1949-50)	.20
Bermuda (Coast & Geodetic Survey)	.75
Fordham	.20
Weston	.20
San Juan	.20
U.S. Navy Hurricane Tracking Stations	
Antigua	.10
Bermuda	.20 & .02
Guantanamo	.20 & .10
Miami	.20 & .02
Richmond	.10 & .05
Roosevelt Roads	.10 & .05
Swan Island	.20
Trinidad	.10
Whiting	.20 & .02

Since the Navy instruments are operated at different drum speeds a greater and lesser error is given for those instruments. The above values refer to accuracy in measurement only. The values for period shown in the report are also affected by sampling. The rather large error for the Bermuda (C. & G. S.) station seems to be largely theoretical since uniform variation trends occurred for this instrument which were always in a direction consistent with that of other instruments.

B. METEOROLOGICAL INFORMATION

1. Storm Parameters

For purposes of correlation of microseisms with marine storms many storm parameters were studied, although they do not all appear in the discussion. The factors studied and recorded are:

(1) position of center of storm

(2) shape

(3) dimensions

(4) maximum wind velocity (observed)

(5) average wind velocity

(6) water depth in vicinity of storm

(7) water depths intervening between station and storm

(8) location of area of maximum velocity

(9) water depth in area of maximum velocity

(10) distance between disturbance and station

(11) pressure gradient

2. Explanation of Weather Charts

Abridged portions of North Atlantic weather charts are used to illustrate the synoptic weather conditions associated with the microseism storms discussed in the three parts of this report. A listing of the seismograph stations marked on the charts is given below.

Key to Seismograph Stations

B Bermuda (Coast and Geodetic Survey)
C Columbia University (New York City and Palisades N.Y.)
F Fordham University
J San Juan (Coast and Geodetic Survey)
W Weston College

Navy Hurricane Tracking Stations

A Antigua
B Bermuda
G Guantanamo
M Miami
R Richmond
RR Roosevelt Roads
S Swan Island
T Trinidad
WH Whiting

The following explanation is given for the symbols used on the weather charts illustrated in this report. Isobars (equal pressure lines) are shown by closed curved lines and are drawn at intervals of 3 millibars. The centers of low pressure areas (cyclones), and of high pressure areas (anticyclones) are indicated by the large letters "L" and "H", respectively. Cold fronts are shown by heavy lines with blackened wedges pointing in the direction of frontal motion. Warm fronts are similar but have blackened semicircles on the side of the line toward which the front is moving. Wind direction and velocity are illustrated by means of arrows which fly with the wind. Each Beaufort wind force unit is indicated by means of a half barb on the arrow. The head of the arrow marks the point of observation. Since frequent and important references are made to wind velocities in terms of Beaufort force and occasionally by means of descriptive terms, a table of wind velocity terminology is given below. The one thousand fathom line is illustrated on the maps by means of a dotted line off the coast.

Beaufort Wind Table

Beaufort Force	Description	Miles (statute) per hour	knots
0	Calm	Less than 1	Less than 1
1	light air	1-3	1-3
2	light wind	4-7	4-6
3	gentle wind	8-12	7-10
4	moderate wind	13-18	11-16
5	fresh wind	19-24	17-21
6	strong wind	25-31	22-27
7	moderate gale	32-38	28-33
8	fresh gale	39-46	34-40
9	strong gale	47-54	41-47
10	whole gale	55-63	48-55
11	storm	64-73	56-63
12	hurricane	above 74	above 64

PART I - FRONTAL MICROSEISMS

A. INTRODUCTION TO PART I.

A series of case histories of microseism storms and the synoptic marine weather conditions existing at the same time are presented below. These cases are fairly typical of a much larger group studied in detail, and enumerated later.

The body of Part I is divided into three sections. Section B deals with frontal microseisms recorded at a single station, Section C, the microseisms recorded at two stations, and Section D contains conclusions derived from the study of frontal microseisms. A slight elaboration of the information to be given under these sections may clarify the presentation.

Section B treats the frontal microseisms recorded at the station maintained by Columbia University, located in New York City in 1948, and at Lamont Geological Observatory in Palisades, New York, in 1949 and 1950. Between September 20, 1949 and January 20, 1950, forty-two distinct cold fronts passed seaward across the northeastern coast of United States. About twelve of these were studied in detail and the histories of six are presented under Section B. Two subdivisions of the records discussed in this section are made owing to an instrumental change during the latter part of December 1949, In Section B-1 are considered records made prior to that date. These records have been made by two independent instruments tuned to 1.3 and 11 seconds, respectively. The former, a single component vertical instrument, recorded directly with an ink-writing penmotor and will be refered to as the "short-period instrument." The latter instruments are three component electromagnetic seismographs recording photographically, and will be referred to as the "long-period instrument."

Under Section B-2, examples of Columbia University records commencing with the latter part of December 1949 are given. About this time the short-period instrument was made to operate off the same boom as the long-period north-south instrument. The intentions were to maintain the short-period characteristic by selective amplification. However, distinct differences between the old and the new short-period records occurred, and seem worth discussing in a separate subsection with an explanatory note here.

Figure 3 shows the apparent response curves of the three instruments just described. It can be seen that the original short-period instrument examined a relatively narrow spectrum of periods. The long-period instrument, and the new short-period one have a much broader range, with peaks of maximum response occurring at different ends of the curves. These facts are of significance since cumulative experience indicates that at a given time a particular seismograph station receives a rather narrow spectrum of periods from a frontal or cyclonic storm, providing uniform depths exist beneath the disturbance. As the front or cyclone recedes, the microseism energy shifts towards higher periods. This spectral displacement appears to cease when the storm has achieved a distance such that uniform water depths prevail. Figure 4 illustrates this frequency shift with time. It follows then that the appearance of recorded microseisms must be a function of both actual microseism characteristics and instrumental characteristics, and any interpretation must take both

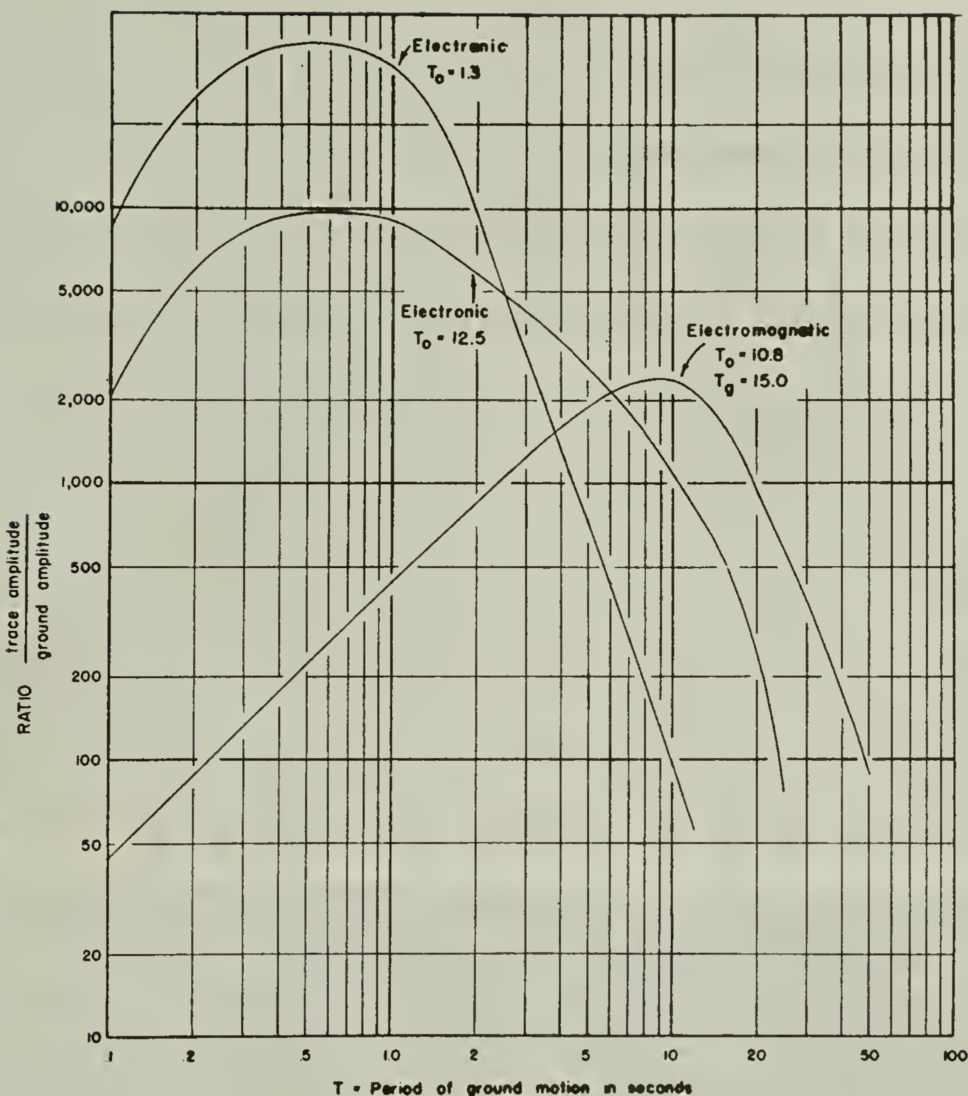

Figure 3. Magnification curves for the Palisades instruments referred to in this report. (The magnification of the electronic short-period instrument used in 1948 was less than than that shown by about a fator of two).

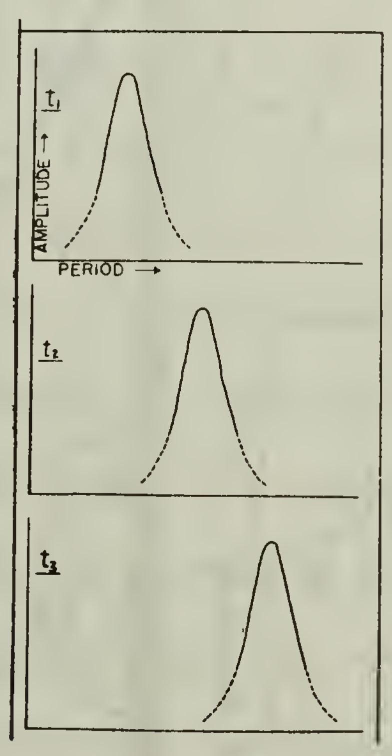

Figure 4. Curves indicating the shift of frontal microseism spectra with time.

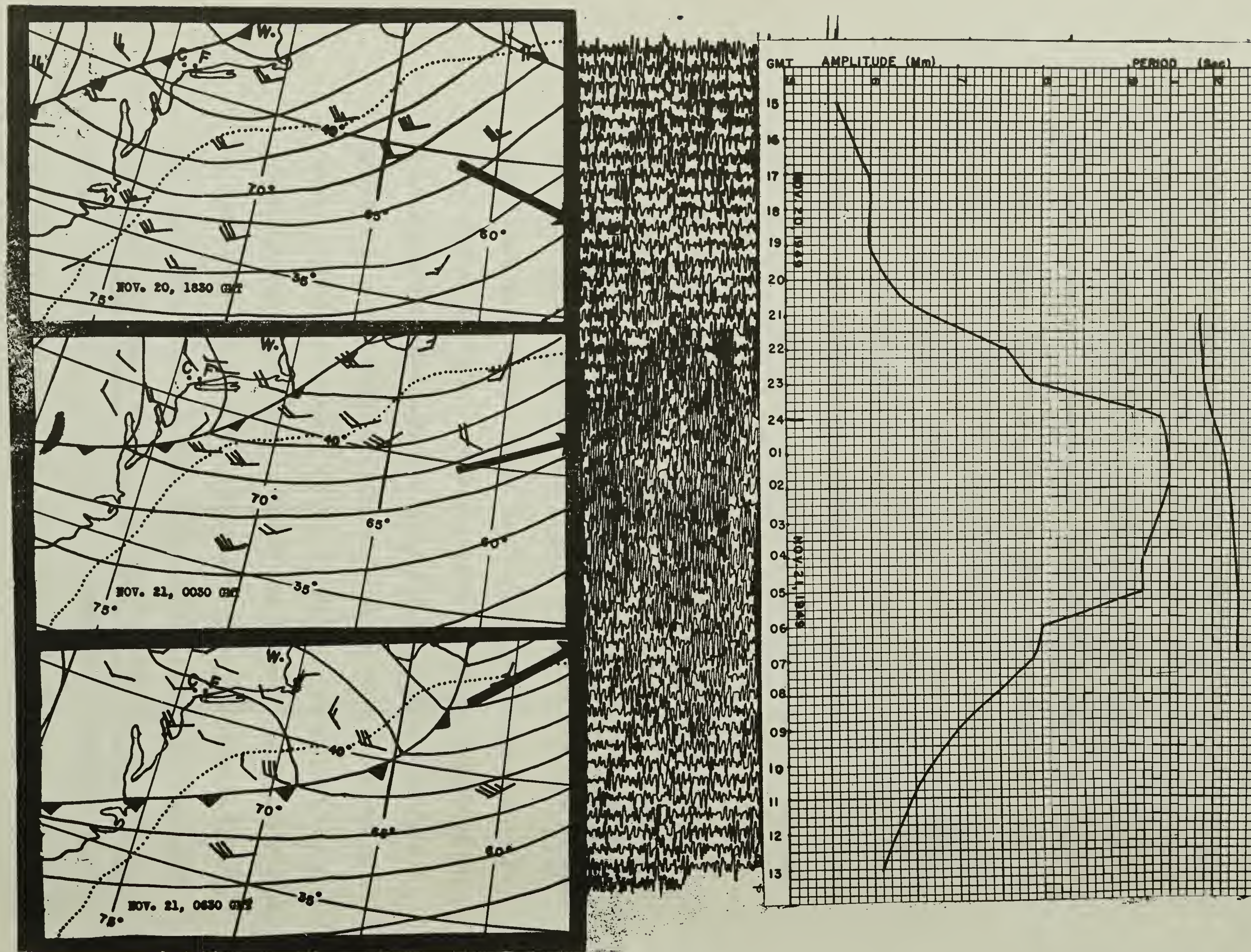

Figure 5. Meteorological and microseismic data for November 20 to 21, 1948.

into account.

In Section C, records made in 1948 at the Columbia University station in New York City and at the Weston College Observatory are compared, together with the associated weather conditions. The Columbia University records are short-period records made by essentially the same instrument as the one referred to in Section B-1 . The Weston records were made by the Weston long-period Benioffs. Unfortunately the difference in paper size, drum speeds and techniques of recording were so great between these two stations at that time that the actual records could not be conveniently illustrated for comparison. Only the graphs of measured microseism conditions are presented. Twenty-five cold fronts and related microseisms were studied for the period from September 1 to December 31, 1948, of which three case histories are given in Section C.

Associated with the microseism conditions illustrated in each case history is a series of related abridged marine weather charts. Although the simplified charts shown give only the wind shifts and velocities associated with the fronts, actual frontal location was also based on discontinuities of temperature, dew point, pressure tendency and clouds. Often weather charts from two or more analysis centers were examined if the location of the front was in any doubt.

B. MICROSEISMS RECORDED AT A SINGLE STATION

1. Columbia University - September to December 1949

a) Microseism storm of November 20, 1949

Figure 5 shows a portion of the Columbia University short-period seismogram from approximately 1400 GMT November 20, 1949 to 1400 GMT November 21, 1949. Adjacent to this seismogram strip is a profile of trace amplitude. Greenwich Mean Time is shown along the Time axis of the graph for both the graph and the seismogram. To the left of the record trace are illustrated portions of three successive six-hourly weather charts of the North Atlantic Ocean. The positions on the seismogram corresponding to the times of the weather observations shown on the charts are indicated by means of heavy arrows.

By interpolating the position of the cold front between 1830 GMT November 20, and 0030 GMT November 21, it seems clear that the rapid increase in microseism intensity occurred immediately as the front passed seaward in the vicinity of Long Island. Further, it appears that maximum intensity was reached prior to the nearest part of the front's crossing the outer edge if the continental slope, as shown by the 1,000 fathom line, and probably while the front was still over the outer portion of the continental shelf. The effect of this front in generating short-period microseisms (from 1.5 to 2.5 seconds) appears limited to action within 300 nautical miles. Also, the relatively small loop over Long Island waters assumed by the front as it passed seaward strongly suggests that microseisms were produced from local conditions over fairly shoal waters, and could not have been the result of more distant portions of the front over deeper water.

The conditions illustrated indicate that special significance should be attached to the narrow frontal zone in considering the generation of microseisms associated with fronts. Prior to the coastal transit of the front a large area of fresh to strong winds - with forces of from 5 to 7 - prevailed over a relatively large area of close coastal waters. Nevertheless the microseism intensity was practically at background or noise level. The wind following the front, as seen on the second and third weather charts is of distinctly lesser force than that preceding the front.

By comparing the times of beginning and of earliest maximum intensity of microseisms on the profile with the times of the first two weather charts an idea of the time necessary for generation of the microseisms can be gained. Clearly the microseisms began to increase almost as soon as the front reached the sea and rose to maximum intensity in from two to three hours. Even this short lag to maximum intensity must depend in great part upon the additional area of the front which crossed nearby waters during this period.

The increase in microseism period of nearly one second shown on the graph is not as evident on the seismogram strip as is the more obvious amplitude intensification. Nevertheless, close examination of the seismogram trace reveals this change even without the aid of the measuring device actually used. A total increase of nearly a second occurs with the most rapid increase being associated with the most rapid amplitude rise. The period increase continued during the decline of the microseism storm, and can thus be correlated with the movement of the front over deeper and more distant waters. Period measurements beyond 0700 could not be continued owing to the merging of storm microseisms with background, and the increasing record irregularity. It can be noticed that a leveling of period had occurred prior to this time, about 0500, and after the front had passed over more uniformly deep waters.

b) Microseism Storm of October 31 to November 1, 1949

Figure 6 compares the Columbia short-period seismogram with the east-west component of the long-period record. To the right of the traces is a graph of amplitudes and periods plotted against time. Each line on the trace shows about two minutes of time.

Figure 7 shows the synoptic meteorological conditions associated with the microseisms recorded between 1400 GMT, October 31, to 1330 GMT, November 1, 1949.

The short-period trace shows two intervals of microseism intensification - a minor development between 1400 to 2400 of October 31, and a larger increase from about 0100 November 1, to the end of the record. These conditions are shown by the solid amplitude cu rve on the graph. The graph also reveals a slight increase in wave period followed by unchanging periods for the lesser disturbance, and a greater increase of almost one second disturbance again followed by a similar constancy of period.

The long-period trace indicates only background or noise level microseisms during the earlier disturbance, but shows well-defined storm microseisms of low amplitude during the time of the second event. Although the amplitude increase here is only about a little more than one half of a millimeter, the trace has distinctly recorded the change from background. The microseism period on this record shows a continuous increase of about one half second.

Consideration of amplitudes and periods recorded by both instruments suggests that maximum energy in the above cases was associated with the short-period microseisms. In the case of the

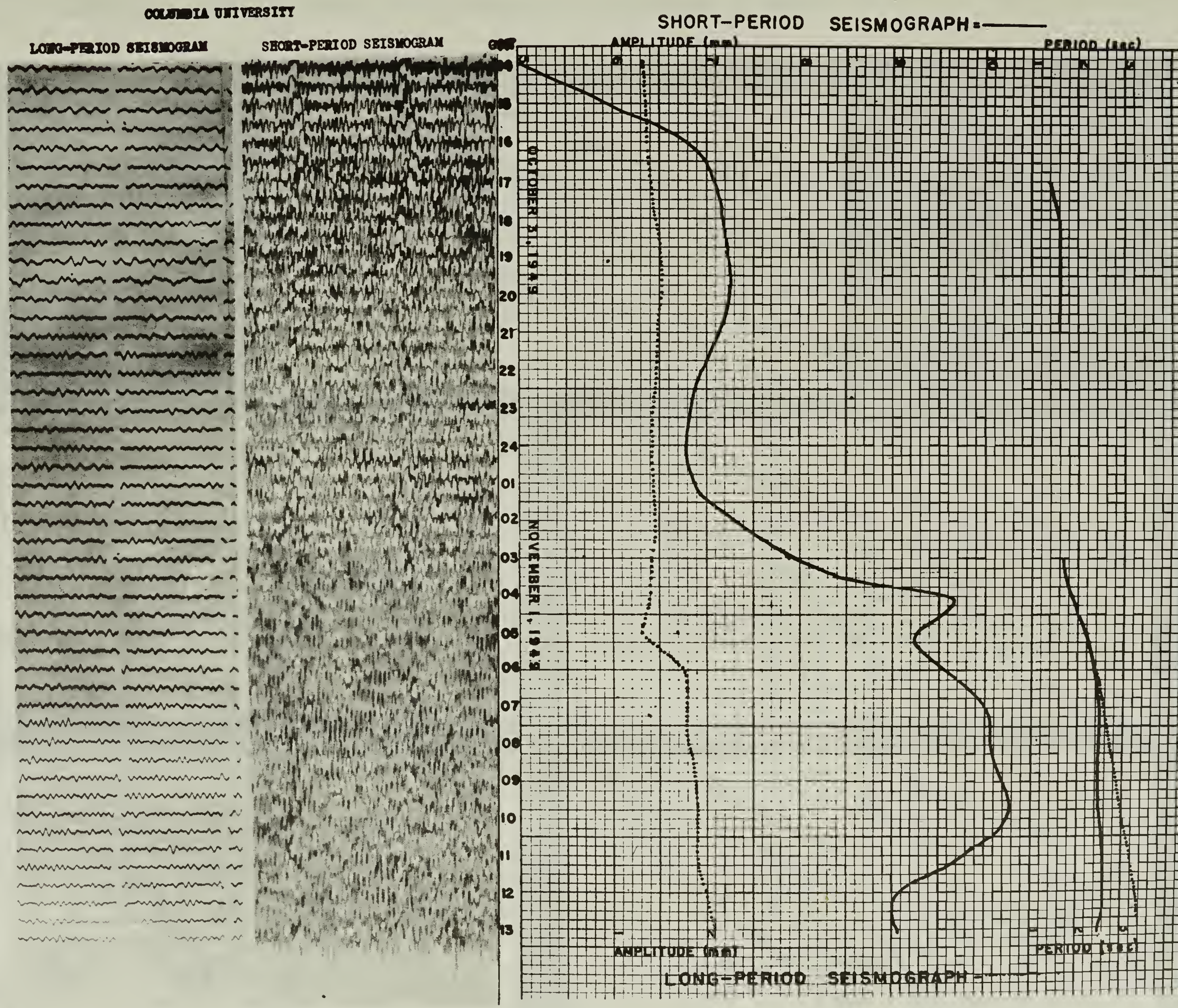

Figure 6. Microseismic data for October 31 to November 1, 1949.

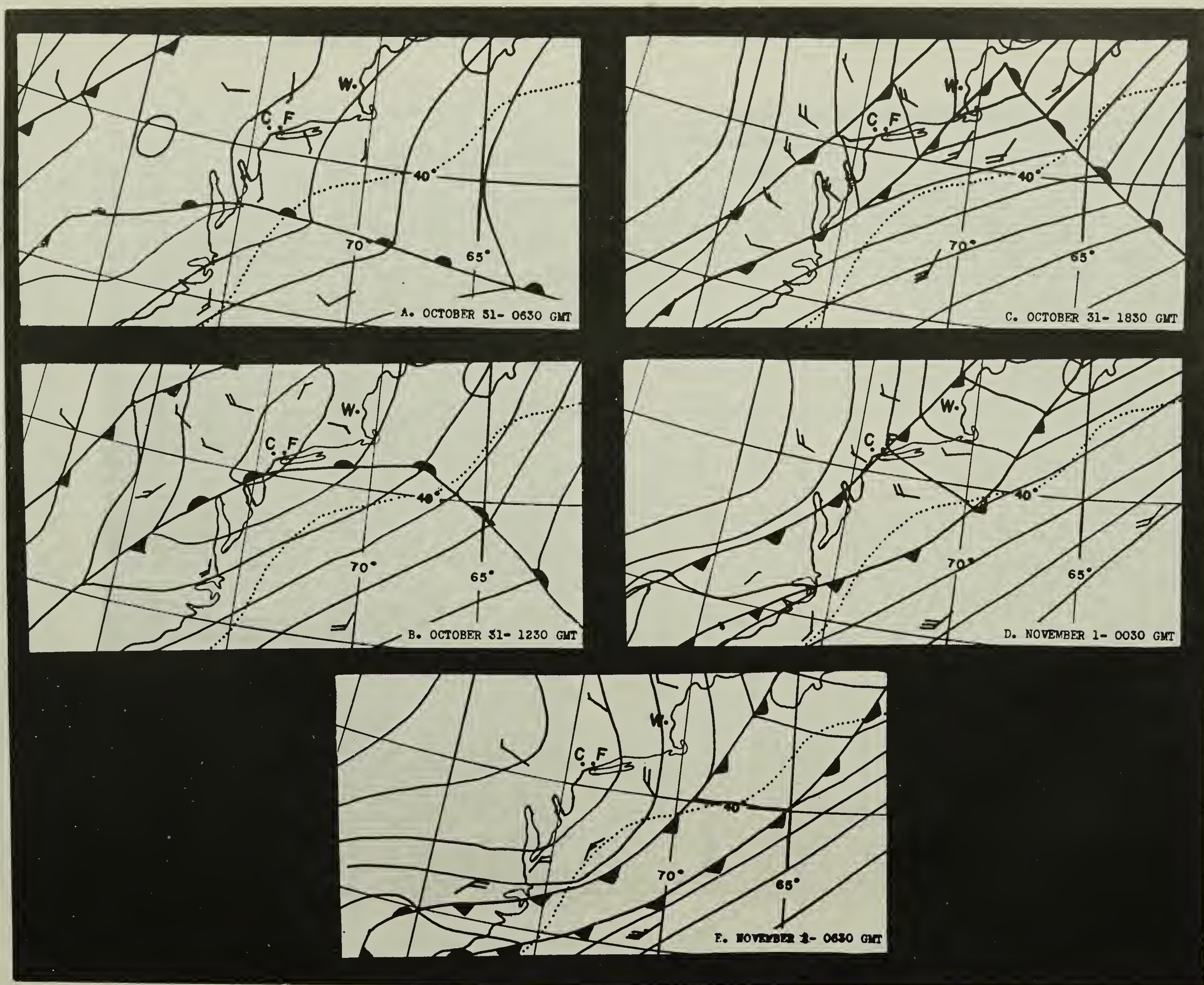

Figure 7. Weather charts for October 31 to November 1, 1949.

earlier, lesser disturbance the long-period instrument was not affected by the microseisms owing to their short period (1.5 seconds) and low intensity at that period.

Study of Figure 7 reveals the marine weather responsible for the conditions just described. Chart "A" is eight hours earlier than the commencement of the seismograms and shows a warm front approaching the station from the south and a cold front approaching over land from the northwest. Six hours later (1230) on "B", the warm front was over waters immediately offshore from the station. The chart still precedes the beginning of the records, which showed background level at the time. According to chart "C" the warm front had begun an eastward motion between 1230 and 1830, becoming a cold front as a consequence, and crossed the station and nearby waters during the intervening time. The microseism increase began about 1400, and appears to have been associated with the transition from warm to cold frontal conditions over waters adjacent to the station. The close warm front prior to this change had little effect on microseism conditions. It further appears very unlikely that a lag of more than one hour was possible between the frontal change and the microseism increase.

Chart "D" shows the second, more vigorous cold front which had been approaching from the northweat, just at the coast line at 0030 of November 1. The time relationship here between the advent of the front over water and the build-up of the microseisms seems very apparent. It also seems clear from the positions of the front on charts "D" and "E" that the first part of the front to reach water was that immediately in the vicinity of the station. Thus the microseisms illustrated must have been produced by the front over close shelf waters.

The situations described above seem to emphasize again the efficiency of the cold front in effecting microseisms of short period at a close station. There is adequate meteorological reason for the support of these observational facts. The maintenance of high microseism intensity as the second front receded was a result of the high winds in the cold air associated with the frontal wave and storm that followed, and which can be seen developing on the southwest corner of chart "E". This storm and related microseisms are given further treatment later under the section of "Cyclonic Microseisms".

c) Microseism Storm of November 16, 1949

Figure 8 presents the microseismic conditions with a weak microseism storm recorded on the Columbia University Palisades seismographs, and the synoptic weather condition over adjacent coastal waters for November 16, 1949.

The amplifier for the short-period instrument was set at a higher than normal gain. This accounts for the prominent, although very irregular noise level of most of the short-period trace, and enabled the weak microseism storm to be detected. At about 1100 GMT, and possibly a bit earlier, the short-period trace shows a distinct, although a rather low intensity, microseism storm. This is manifest by the regular wave groups of very short period which are fairly obvious beginning with the 1100 line. The measured wave period at 1100 was 1.6 seconds. This increased to 1.8 seconds at the end of the record. These waves are distinguishable from the background not so much

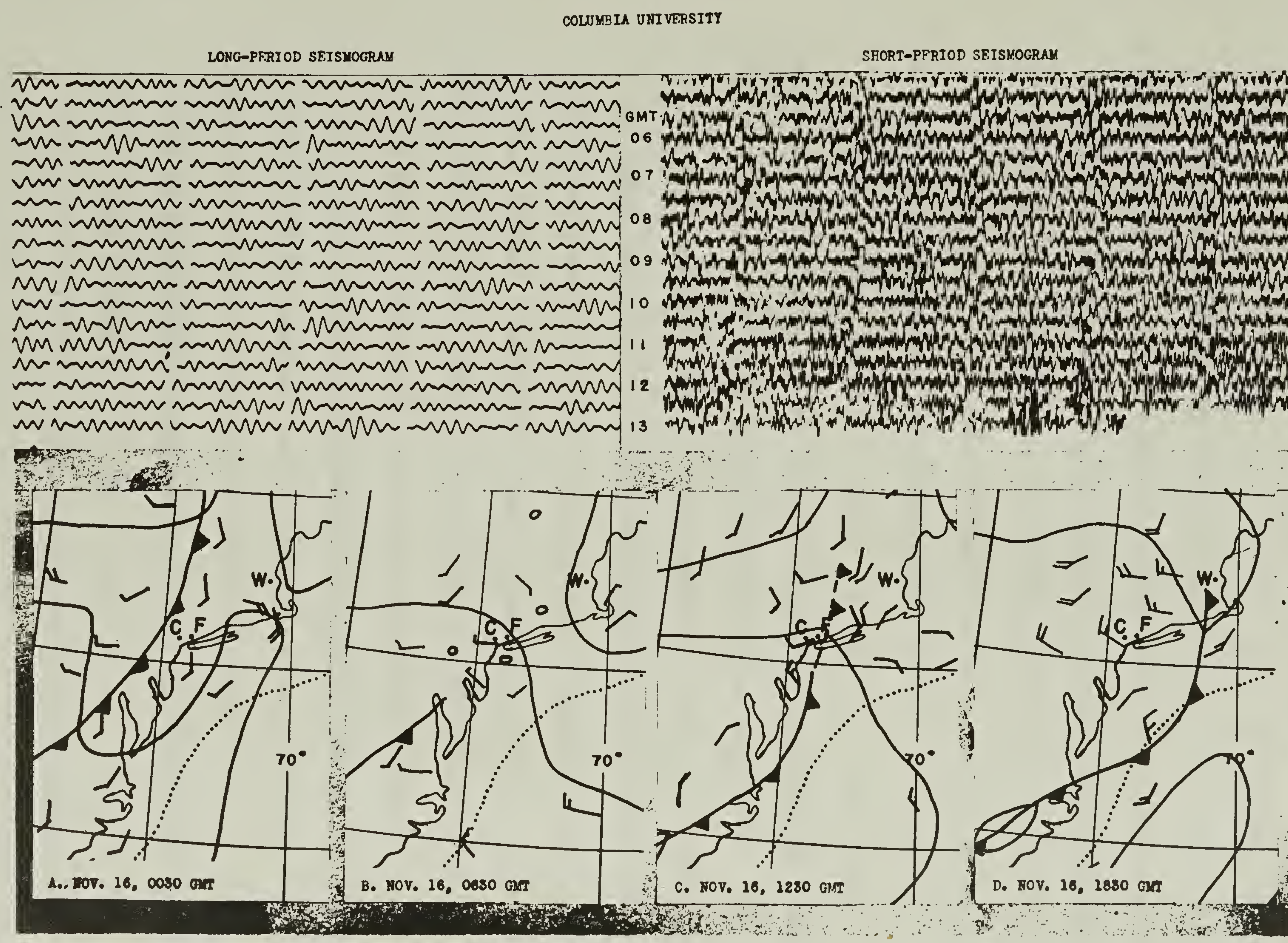

Figure 8. Meteorological and microseismic data for November 16, 1949.

by noticeable amplitude increase, as by their regularity and very short period.

The long-period trace shows no response to these microseisms. The large, regular waves on this record have been correlated with a distant, intense North Atlantic storm, and will be discussed in detail in the following section on North Atlantic storms and related microseisms.

Four six-hourly weather charts are shown in the lower part of Figure 8. Chart "A" shows an inland cold front extending continuously approximately parallel to the coast line. Very light winds (Beaufort of 1 to 2) are associated with the very flat pressure field preceding and following the front. In fact the air masses on either side of the front appear so nearly homogeneous (from the wind conditions shown, and other weather elements not shown), that the northern portion was not located on Chart "B", at 0630. The circles on this chart indicate stations experiencing calm air. This occurs again on Chart "C" at 1230, where no pronounced discontinuities exist north of the continuous frontal line. In view of the position of the northern section of the front located on Chart "D", at 1830, the writer has shown the possible continuation of the front on Chart "C", at 1230, by means of a broken line. The weak wind shift on either side of this line offers justification for this.

In view of the microseism storm which began between 1000 and 1100 on the short-period record, it appears that the front must have existed. As such, the recorded microseisms commenced when the front had barely traversed the closest adjacent waters.

Experience shows that the calm to light winds preceding and following the front could not have generated the recorded microseisms. This, together with the time relation indicated above again suggests possible pressure fluctuations or turbulence in the frontal zone itself as the generating factor. Admittedly, the front was weak as shown by the low amplitude of the microseisms even at relatively high gain.

2. Columbia University Records - December 1949 to January 1950

a) Microseism Storm of December 28, 1949

The seismic and meteorlogical conditions associated with the cold front passage of December 28, 1949 are illustrated in Figures 9 and 10, respectively. It can be seen that the microseisms of the short-period instrument (solid line) showed a marked increase in amplitude between 0600 and 0700 at which time the cold front in question was off the eastern end of Long Island. This microseism storm, as recorded by both instruments, reached maximum amplitude during the following four hours. At this time the nearest part of the front had probably cleared or was close to the vicinity of the one thousand fathom line. This can be seen by interpolating frontal positions for times between the times of charts "B" and "C".

The first measureable response of the long-period instrument occurred between 0800 and 0900. Actually, a discernable response of different period and regularity from that of the background, although of very low amplitude, existed for a couple of hours earlier.

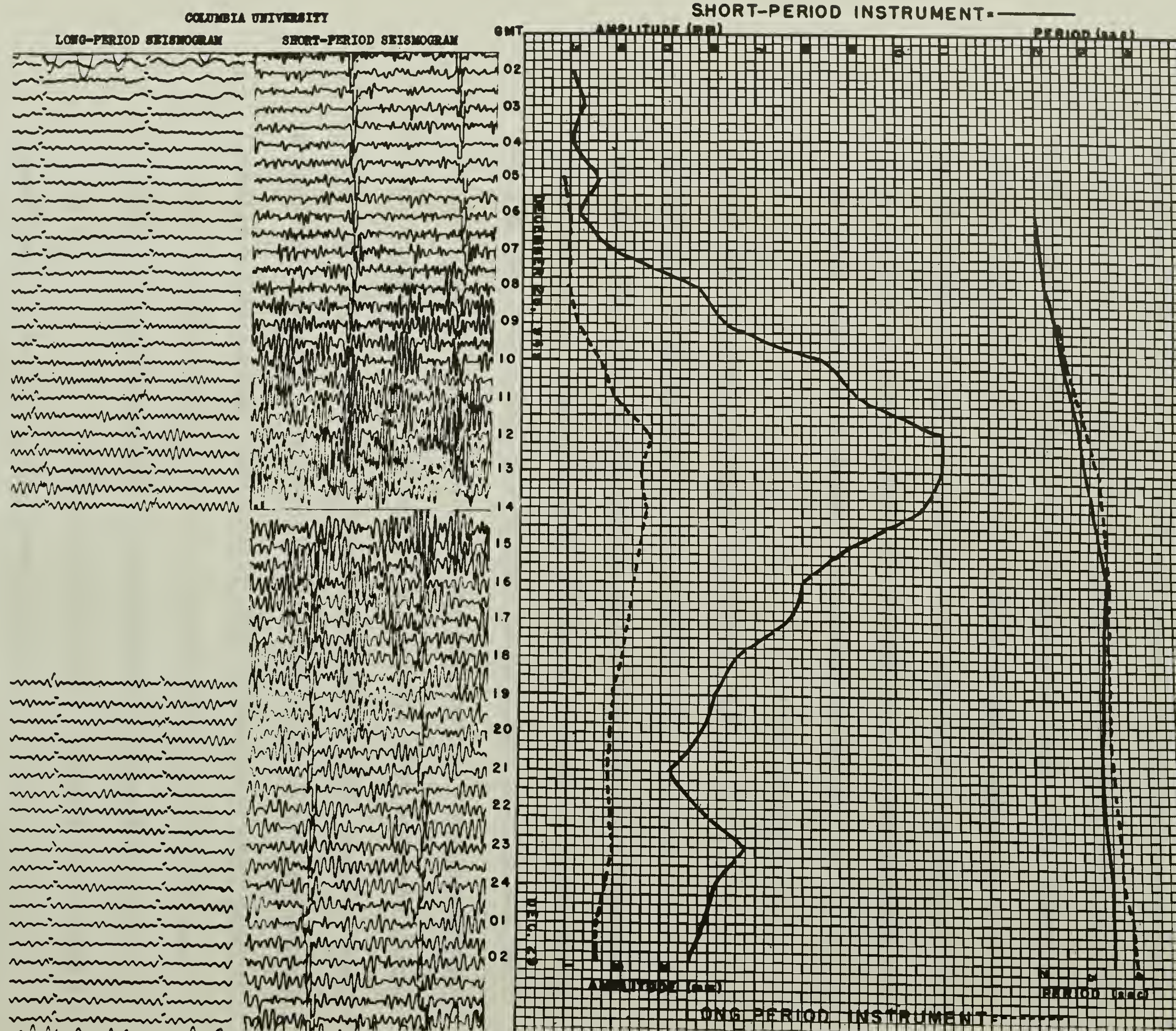

Figure 9. Microseismic data for December 28 to 29, 1949.

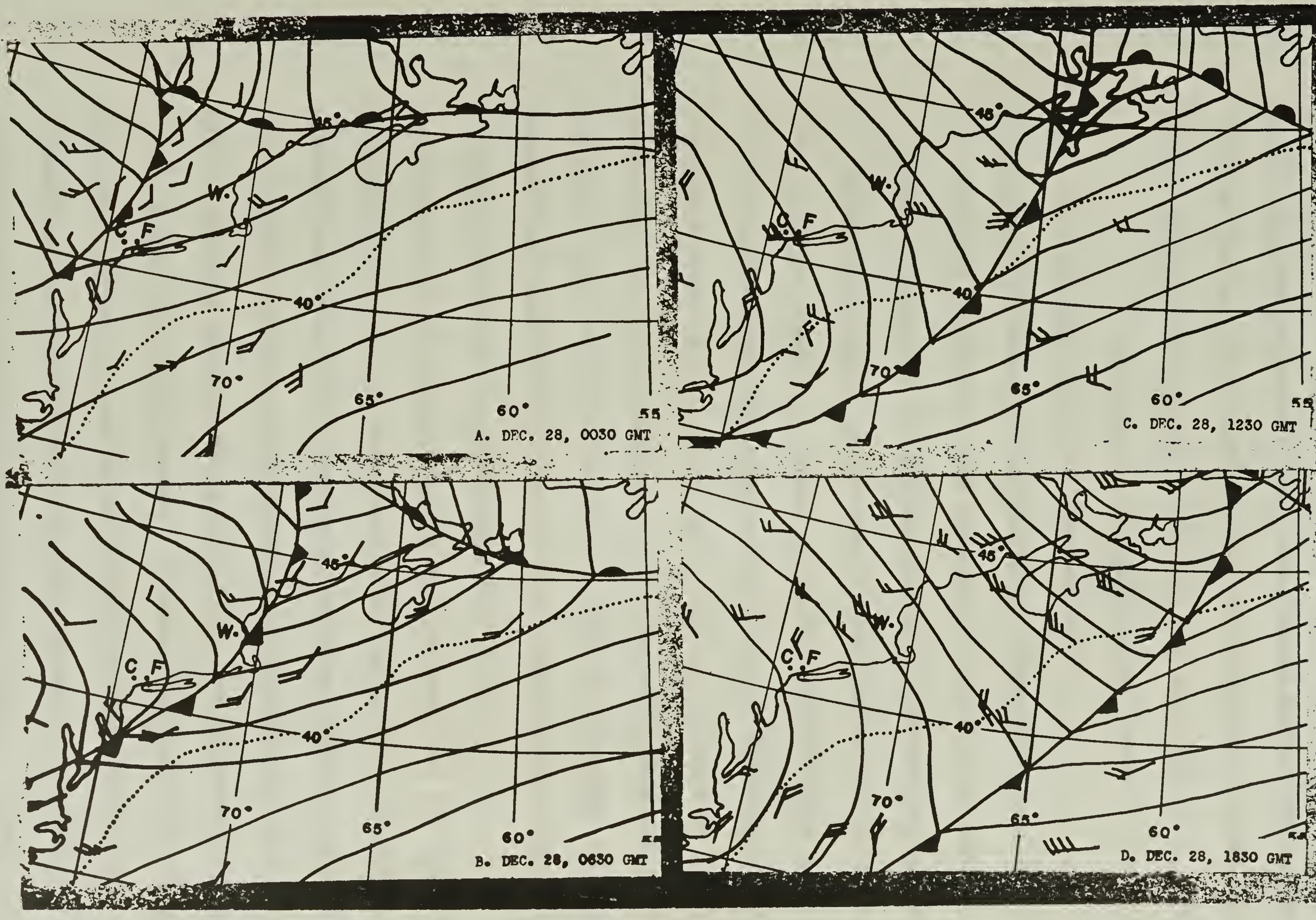

Figure 10. Weather charts for December 28, 1949.

The graph shows that the curves for microseism periods are nearly identical, commencing between 2.0 and 2.5 seconds, and becoming nearly level at 3.6 seconds after 1600. By this time the cold front had passed entirely across the one thousand fathom line into deep water.

The observations given indicate that the new Columbia University short-period instrument (operating off the same boom as the long-period N-S instrument) essentially emphasized the threshold microseisms of 2.0 to 2.5 seconds recorded by the long-period instrument, thereby permitting better study of this frequency range. A visual comparison of the microseisms recorded by the short-period instrument described here with those described in Section 1, above clearly shows the difference in initial response of the two instruments. Earlier threshold periods were distinctly near 1.5 seconds, and occurred with the front over close and restricted shoal waters.

It is significant that the first response of even the short-period instrument occurred in this case when the nearest part of the front was about 75 to 100 miles from the station. Further, maximum intensity of the storm occurred when the front was over deeper, more distant waters in contrast to maxima occurring over shelf waters and at lower periods for the storms described in Section 1. More specifically, the period at the time of maximum for this storm was 3.0 seconds compared to the 2.0 to 2.5 second periods associated with the maximum microseisms of closer origin described earlier. These facts further indicate the shift of microseism energy toward longer periods with time, as water depth and distance of the generating area increase. It is also noted for this storm, as in the case of the storms in sub-section 1, that the graphical curves for period became level when the fronts had crossed over waters of greater and more uniform depth beyong the continental slope.

b) Microseism Storm of January 7, 1950

Figure 11 presents the seismic and meteorological conditions during the first half of January 7, 1950. The seismic situation as recorded by the Columbia University Palisades seismographs is illustrated by portions of the long-ans short-period traces. The measured amplitude and period values are illustrated on the graph to the right. The three weather charts summarize the marine weather for the same interval and show the cold front responsible for the microseism storm.

It is noted again that the short-period instrument was more responsive to the s eismic disturbance, showing first measureable response at 0900 compared to the first measureable long-period activity at about 1030 to 1100.

Preceding the microseism storm the long-period trace shows distinct long-period waves of relatively high amplitude. These are the result of a distant intense storm and will be discussed in Part II on North Atlantic Storms. This trace indicates the new microseism storm of frontal origin by the low amplitude, short-period waves superimposed on the above mentioned longer waves. Thus, a greater irregularity of t he record occurs after 1000. It was these small, new waves that were selected for measurement on this record.

The two sets of waves just described, s eem by their presence to be of distinct significance. First they show the long-period seismograph has a response covering a broad spectrum of periods, at least from 2.5 to 6 seconds, and that the response is greater for the long-period microseisms. The latter is concluded from the higher amplitude of the longer-period microseisms generated by very distant cyclonic storm, in contrast to the low amplitudes of the frontal microseisms of much closer origin. On the other hand, the response of the short-period seismograph is distinctly greater for microseisms of short period, than the longer-period instrument, although the first half of the short-period trace also shows the longer cyclonic microseisms showing through the background noise.

A second fact of significance is apparent from the records. Only two distinct sets of microseisms of very narrow period spread are exhibited by the long-period seismogram, yet the instrument is capable of recording microseisms of intervening periods as well as those much longer than 6 seconds. This suggests very strongly that at a particular time a narrow spectrum of periods is received from a frontal or cyclonic generating area. It will be shown later that this is not true for meteorological disturbances over a water environment of very variable depths.

By interpolating the cold front position between the 0630 and the 1230 maps it is estimated that the frontal microseism storm commenced with the nearest part of the front a short distance beyond the eastern tip of Long Island, while still over shelf waters.

The microseism storm increased slightly in intensity and noticeably in wave period following the termination of the record under consideration. This was a consequence of the

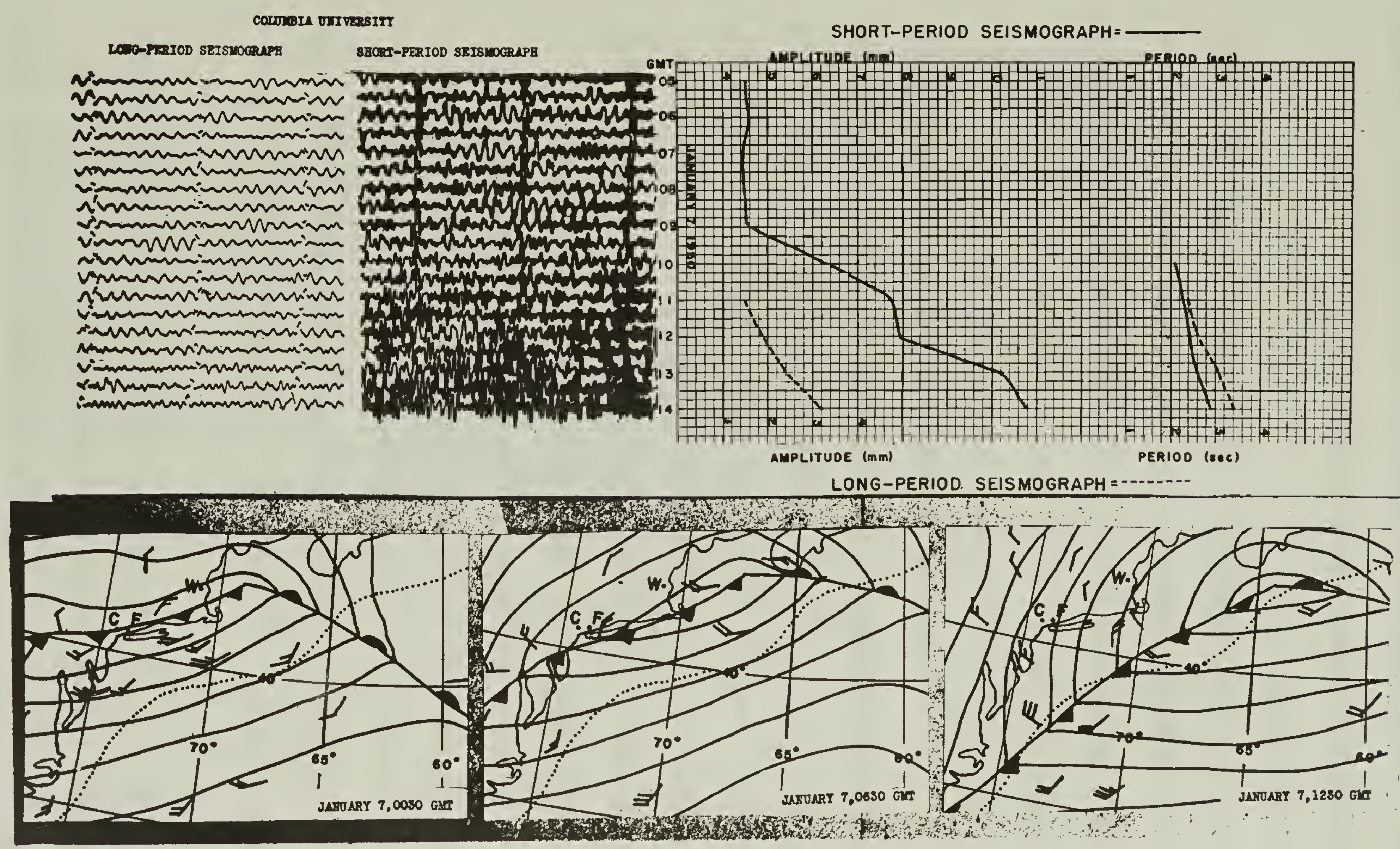

Figure 11. Microseismic and meteorological data for January 7, 1950.

broad area of strong cyclonic winds associated with the cold air mass following the front. This cyclonic effect is treated more completely in Part II.

It is worthy of note that the observed winds preceding the coastal passage of the cold front were of force 5 over a fairly large area yet no noticeable microseism disturbance resulted until the front reached the coastal waters.

c) Microseism Storm of January 16, 1950

Figure 12 illustrates the meteorological and the resulting microseismic conditions for the latter half of January 16, 1950. The earliest frontal microseisms recorded by the short-period instrument appeared at 1800. The trace at 1900 on the long-period record shows the first response for the corresponding instrument. The nearest part of the cold front at 1800 was about 50 miles east of the eastern end of Long Island.

The threshold period for the short-period instrument for this storm was about 2.2 seconds. The corresponding measurements for the long-period instrument were not plotted on the graph. However, the relation between the two instruments in this case is identical with those of the two previous cases.

On the long-period trace the microseisms of frontal origin are easily detected after 1900 by their shorter period and lower amplitude than the preceding larger waves which have been correlated with a much larger, and much more distant cyclonic storm in the North Atlantic. It is again significant that a narrow spectral band of periods appears to be associated with both the microseisms of distant cyclonic origin on the

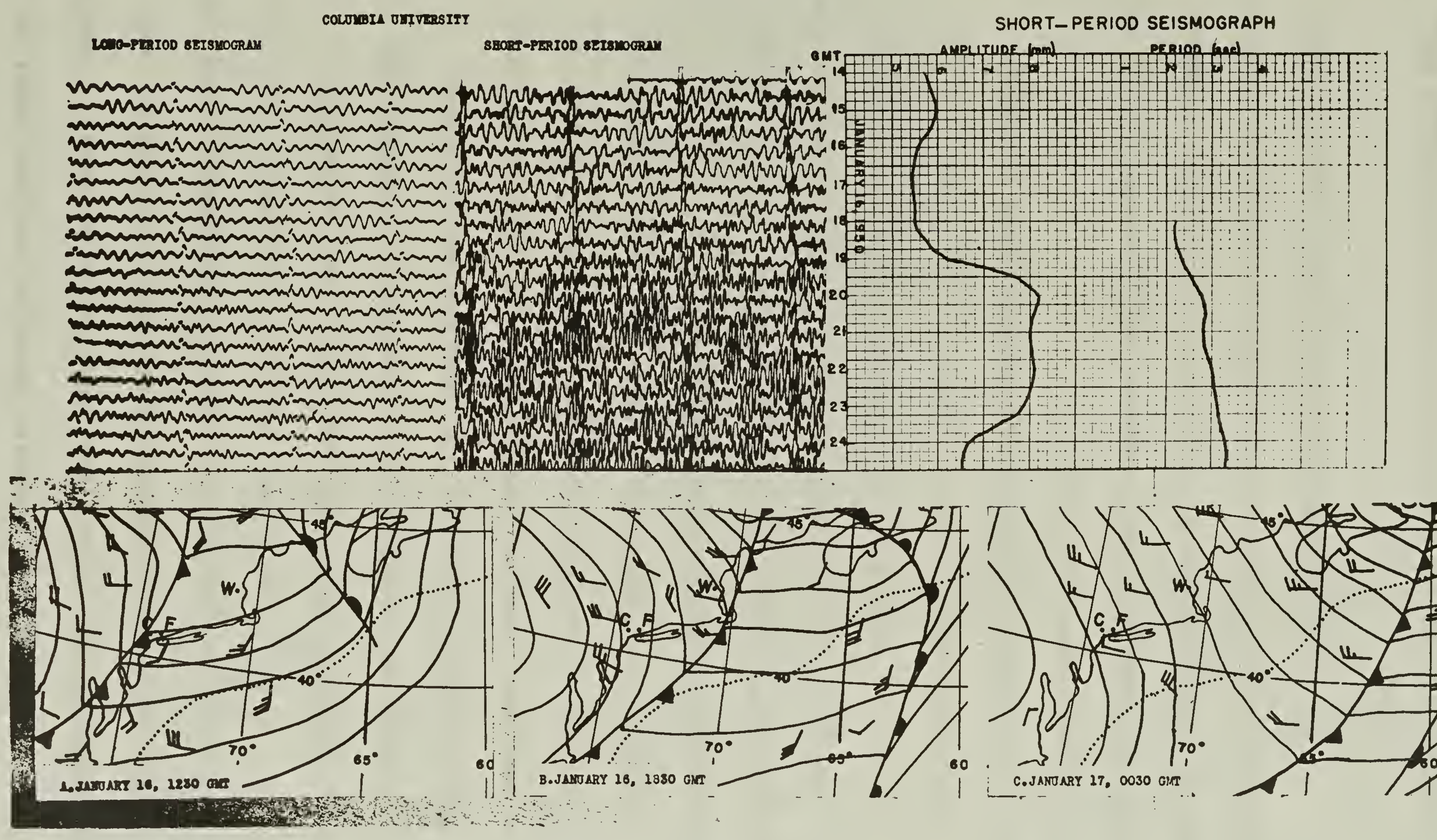

Figure 12. Microseismic and meteorological data for January 16, 1950.

early section of the record, and those of close frontal origin, under discussion. This is similar to the case considered just above.

Also noteworthy is the fact that the southerly winds over coastal waters preceding the cold front passage were fresh to strong (force 5 to 6) over a large water expanse. The recorded microseism storm commenced with the passage of cold front conditions across the coast.

C. STUDIES OF FRONTAL MICROSEISMS RECORDED AT TWO STATIONS

1. Microseism Storm of September 21, 1948

Figure 13 illustrates the synoptic meteorological conditions for September 21, 1948, together with a graph of measured microseismic conditions as recorded by the Columbia University and Weston College seismographs.

It can be seen from the weather maps that the cold front shown extended east-west, and moved southerly across the southern coast of New England. As such, this front differs in position and direction of motion from the cases discussed heretofore, and must have crossed the Columbia and Weston stations and adjacent waters nearly simultaneously.

The amplitude curves on the graph show that the response of the short-period Columbia instrument (solid line) to the microseism storm commenced about two hours earlier than that of the long-period Weston instrument (broken line). Similarly, the time of maximum of the Columbia record is reached prior to that of the Weston record. (The Columbia University long-period instruments were not functioning in 1948 and the Weston Observatory has no short-period instrument equivalent to that of Columbia for purposes of comparison.)

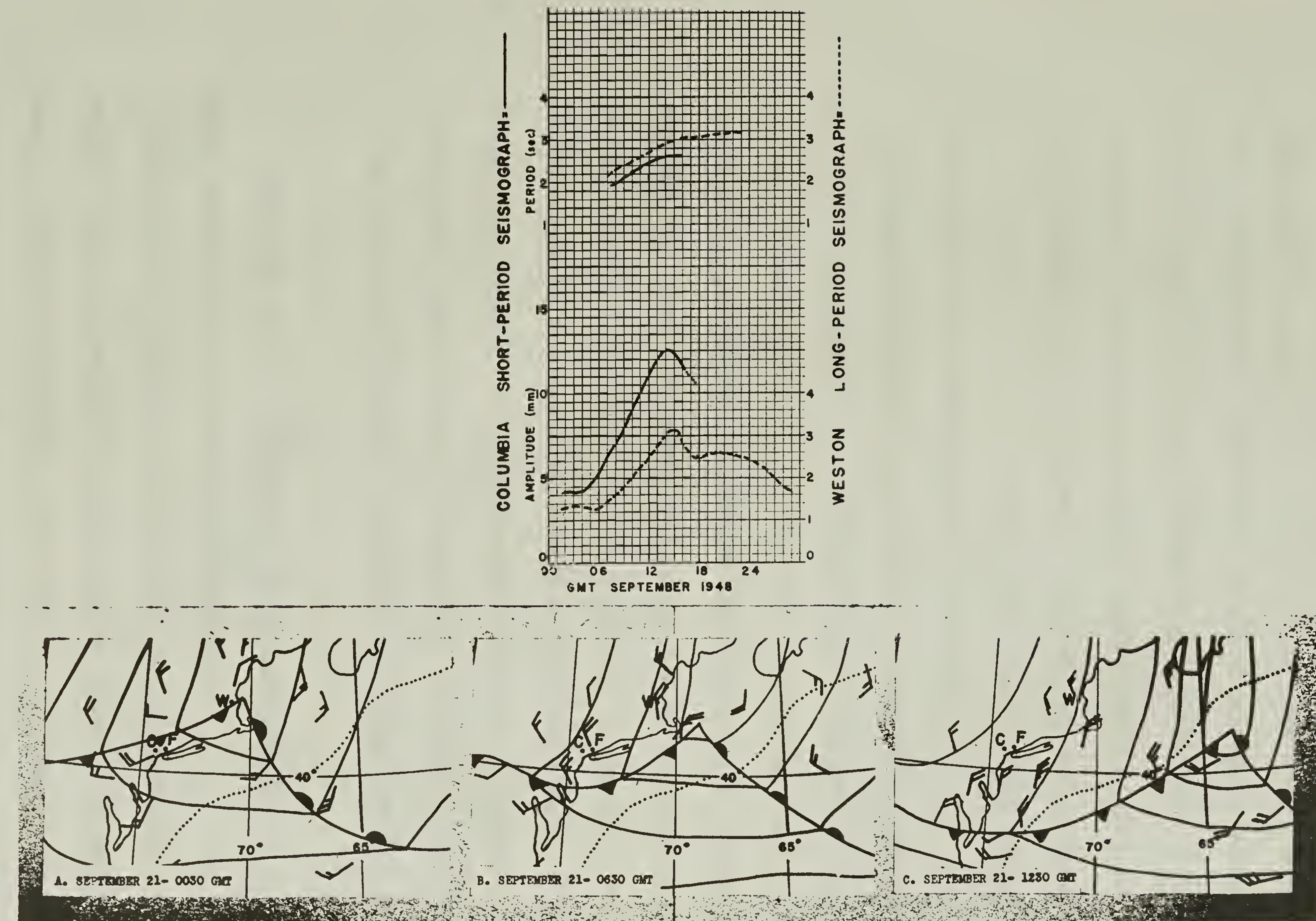

Figure 13. Microseismic and meteorological data for September 21, 1948.

The periods of the microseisms recorded by the Weston instrument are from 0.3 to 0.6 seconds higher than those recorded by the Columbia instrument. It seems worthy of note again, that following maximum intensity of the microseism storm the period trend became level or nearly so. This occurred subsequent to the front's crossing the continental slope as indicated by the 1000 fathom line.

The time of commencement of the microseism storm on the short-period Columbia University Seismogram can again by related very nearly to the time of transit of the front across waters immediately offshore from southern New England and Long Island. This can be determined by interpolating the frontal positions for the times between the times of charts "A" and "B". A lag is noted in the response of the long-period Weston instrument. The relationship of response to the front of the short-period Columbia University Seismograph and the long-period Weston Seismograph is much the same as the relations noted earlier between the short- and long-period instruments at Columbia University.

2. Microseism Storm of November 11 and 12, 1948

The seismic and related meteorological conditions for November 11 and 12, 1948 are presented in Figure 14. The Columbia University short-period seismograph amplitude curve (solid line) shows a very steep rise commencing at 0000 and reaching a maximum at 0600, on November 11. The longer-period Weston instrument record (broken line) shows the increase in amplitude beginning about three and one half hours later, or at 0330. Similarly, the Weston maximum occurred at about 1000, and did not

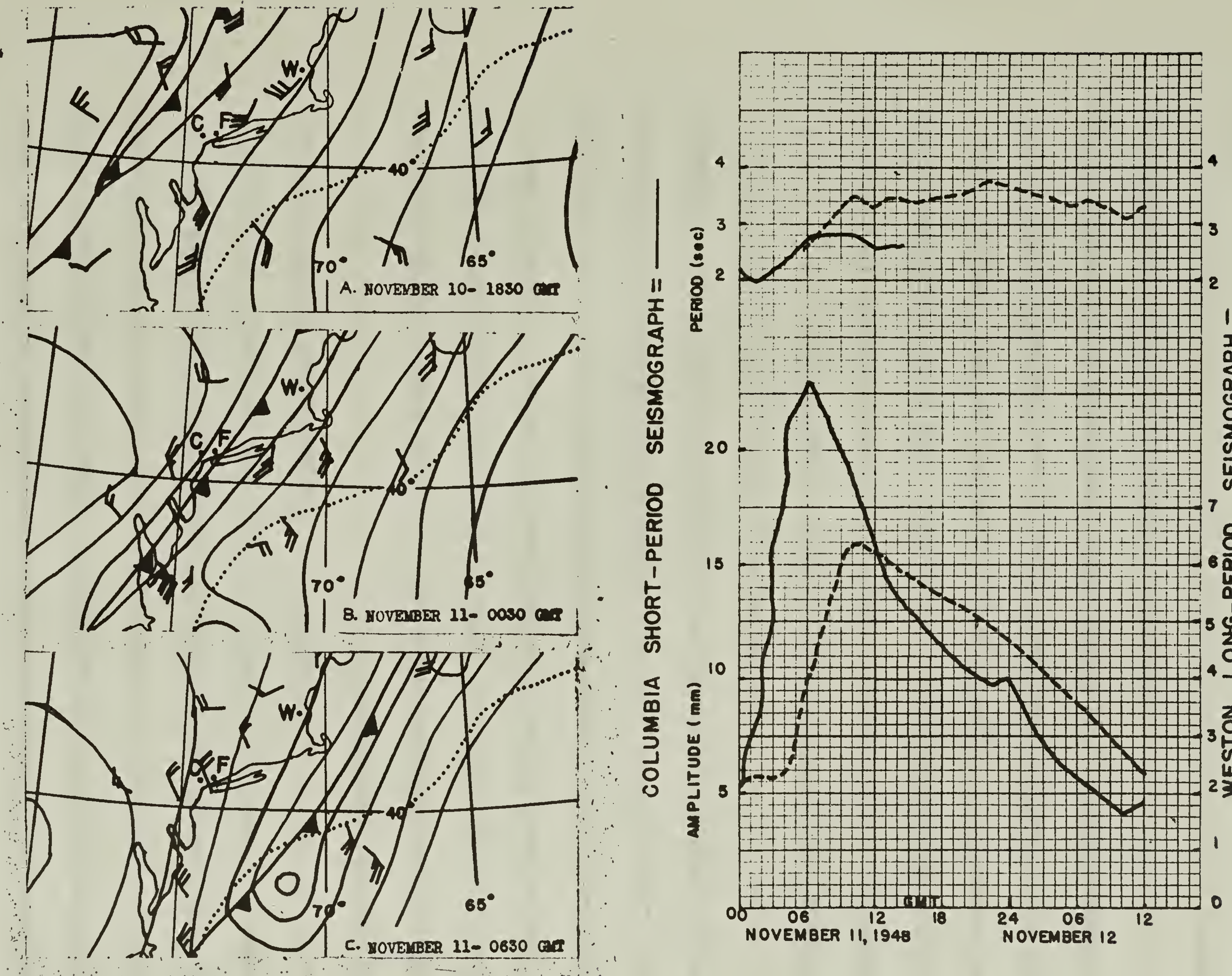

Figure 14. Meteorological and microseismic data for November 11 to 12, 1948.

reach background level until the same interval after the Columbia curve.

Inspection of charts "A" to "C" reveals that the short-period microseism storm commenced almost simultaneously with the passage of the front over waters immediately adjacent to the station. The area of water disturbed by the front at this time was undoubtedly very restricted. The first response of the Weston instrument did not occur until the front was at a greater distance and occupied a larger deep water area.

The velocity of the front, in addition to the high winds attending it, indicate it to have been a vigorous one. This explains the high maxima of 23 and 6.4 millimeters on the Columbia and Weston instruments respectively, which are higher values than those noted in preceding cases. It again seems worthy of note that the force 6 winds with a long south to north fetch in the warm air preceding the front had no apparent effect on microseism behavior.

It appears of further significance that the curves for period, although of different magnitude, show much the same trend, becoming nearly level after a sharp rise to maxima. Note that the period maxima correspond to the amplitude maxima as shown by the respective curves. In each case the flattening of the period trend coincides with the passage over deep water of the part of the front nearest to each station.

3. Microseism Storm of December 6 to 8, 1948

Figurd 15 illustrates a graph of the seismic, and weather maps of the meteorological conditions for December 6 to 8, 1948

The relatively low amplitude maximum of the Columbia short-period instrument (solid line) from 0000 to 0600, December 6, corresponds exactly in time to the passage of a sharp wind-shift line across waters adjacent to the station. This wind-shift marked the crest of a ridge of high pressure present along the coastline, which appeared on the weather maps 12 and 6 hours respectively earlier than chart "A". The Weston instrument showed no response to this phenomenon which had weakened considerably before traveling eastward to a point where longer period microseisms could be generated. Owing to a smudging of the pen recorder it was impossible to measure periods on the Columbia records for the entire interval under consideration here.

The second, larger microseism disturbance can be correlated with the cold front shown on charts "A" to "C". The Columbia amplitude curve shows a first rise from 1200 to 1700 on December 6 and then a much steeper slope commencing with 1700. According to Chart "A", a weak cold front passed over closest station waters at 1200 to 1230. In addition to the other weather parometers on the original map, the front here seems definitely indicated by the wind shift from southeasterly preceding the front to southerly and southwesterly following it. This front, which was distinct on several maps preceding chart "A", dissolved after crossing Long Island and was no longer discernable. The steeper Columbia amplitude slope after 1700 coincides exactly with the eastward passage of the main and more vigorous cold front to the west over the nearest coastal waters.

The amplitude curve of the long-period Weston instrument shows its rise in response to the second front about

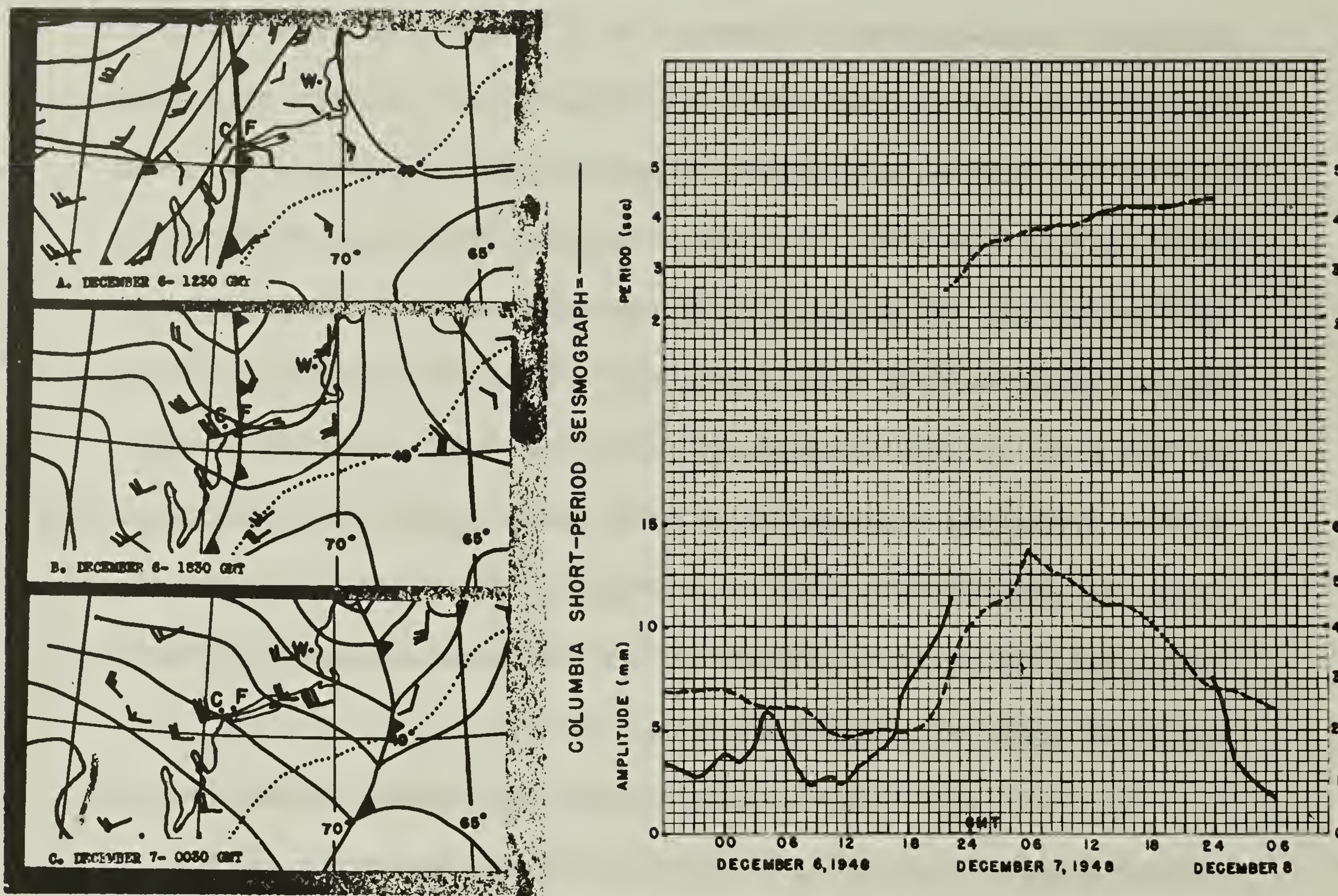

Figure 15. Meteorological and microseismic data for December 6 to 8, 1948.

three hours later - or at 2000 of December 6. The weaker, earlier front apparently had no effect on this instrument.

The gap in the Columbia record represents an interval in which the instrument was dead. Both amplitude curves nevertheless indicate a rather prolonged microseism storm of 42 hours. Charts "B" and "C" show that winds of Force 6, Beaufort, followed the main front and actually persisted for the interval shown by the microseism storm. Thus, although the commencement of the disturbance can be related to frontal position, the time and magnitude of the maxima and conclusion were probably more a function of the relatively large area of "cold" cyclonic winds.

D. CONCLUSIONS REGARDING FRONTAL MICROSEISMS

1. The relatively narrow frontal zone of cold fronts appears capable of generating microseisms through some coupling mechanism at the sea surface.

2. Microseism storms of frontal origin are generated very soon after a cold front passes seaward from the land, and while the front is over relatively shoal and very restricted waters.

3. A rather narrow spectrum of periods appears to be generated by a front at a particular time.

4. As the front recedes, with distance and depth of water increasing, the spectrum of periods shifts, with periods becoming greater. Very short-period microseisms (1.5 to 1.6 seconds being the shortest observed with available instruments) are recorded when the front is over close, shoal waters. Periods become fairly constant after fronts have crossed onto waters of greater and more uniform depth beyond the continental slope. This suggests depth as a significant factor in microseism

generation. In the cases of microseisms attributed only to frontal origin, and not affected by fresh to strong cyclonic winds that often follow a cold front, periods become constant at 2.6 seconds for the short-period seismograph and from 3.0 to 3.5 seconds for the long-period instrument. With several sharply-tuned seismographs and microanalyses of synoptic surface weather charts, a quantitative relationship microseism period and frontal position may be deduced.

5. The narrowness of the frontal zone which appears capable of generating microseisms suggests that pressure fluctuations or turbulance in the zone is at the root of such microseism origin. Measurements of submarine pressure variations beneath cold fronts and other violent storm areas may reveal more complete data bearing on the origin of microseisms.

6. Nearly all the microseism storms presented, and many others studied, show a characteristically symmetrical rise and fall of intensity as shown by the rather sharp-crested graphic curves for amplitude. It is suspected that for each front, depending in its strength and width, there is for each recording station some optimum position in which conditions of strength, width, and area of water covered combine to give maximum microseism activity. There is thus a uniform increase in intensity until that point, followed by a corresponding decrease, as distance increases.

7. As a front recedes, microseism intensity may be maintained at a high level by fresh to strong cyclonic winds which may follow the front. It seems significant that winds of similar strength in the warm air preceding a cold front have no

noticeable effect in the production of microseism storms. This further suggests the effect of gustiness or turbulence as being of special significance in microseism origin.

8. The microseism storms resulting from cold fronts are among the most regular that have been observed. By regularity is meant (1) symmetrical groups of microseism waves building up to a peak, and then decaying, (2) a relatively large number of waves per group, and (3) a very narrow period spectrum associated with the microseism waves. Nearly all the frontal microseisms illustrated above show these features except where lines have overlapped from high intensity, or where cyclonic wind conditions followed the front. Figure 16 compares such regular frontal microseisms on the Columbia University (Palisades) original short-period seismogram with the record on the following day of hurricane microseisms generated by a storm south of Newfoundland. This appears to oppose Gilmore's findings (2,4) in connection with frontal microseisms generated near the Florida coast. It appears that the regularity is a function of the environment of generation rather than of the type of meteorological disturbance. The limited area of fronts together with the approximate parallelism to the coast of those discussed here, resulted in microseism generation in waters of uniform depths. The irregular hurricane microseisms were produced by a storm of greater area and over variable depths. The diversity of water depths in the vicinity of the southern Florida coast may thus account for the irregular pattern of frontal microseisms noted by Gilmore.

9. The importance of surface wind waves and swell in producing microseisms seems to be negated by the following observations:

a) The abruptness with which microseisms commence after a front or strong winds disturb the sea.

b) The decay of microseism storms as a front recedes despite the increasing area of surface wave generation following the front.

c) The fact that long-continued moderate to fresh and strong winds (force 4 to 6) off the east coast preceding a cold front have little effect in producing microseism storms, yet it has been shown by Donn (5) that such winds in this area produce prominent ocean surface waves with periods from 6 to 10 seconds. According to Deacon (6), and Darbyshire (7), microseisms are the product of interfering surface waves and have one-half the period of such waves. Banerji (8) has related 10 to 30 second microseisms with local shallow-water swell of the same period in the Indian Ocean. Neither of these findings is in accord with the observations presented.

10. Although no direct attempt has been made to correlate microseisms with local surf conditions, the evidence presented seems to negate any such origin. Vigorous cold fronts that transit from land to sea in this area, especially when followed by strong westerly winds usually damp surf conditions to very low or no activity. Yet these are the conditions that produce the most prominent microseisms from local weather. Also, experience so far accumulated suggests that surf would produce micro-

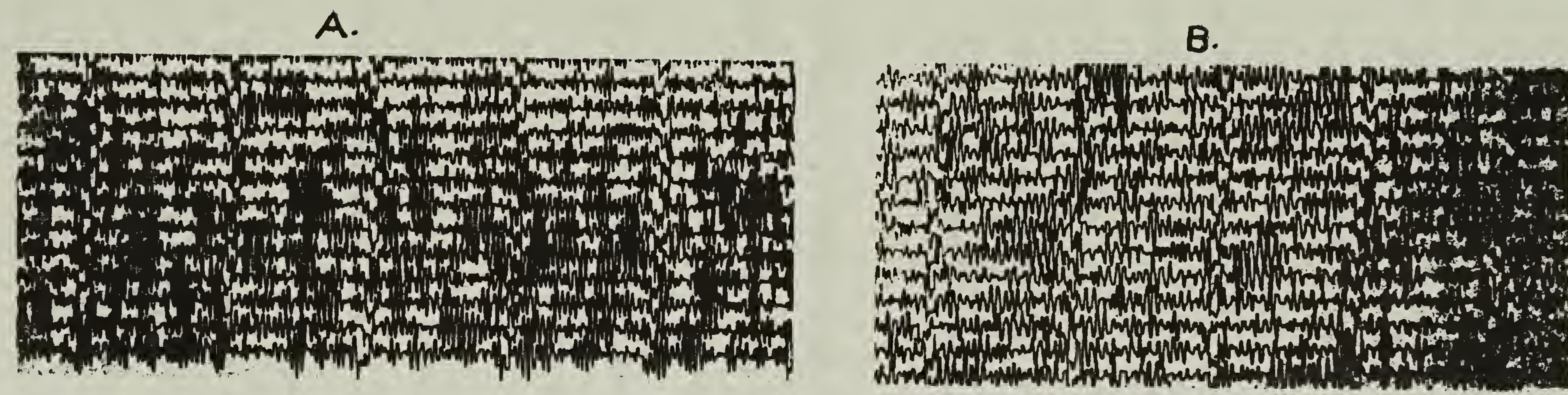

Figure 16. Comparison of regular frontal microseisms "A" with less regular hurricane microseisms, "B".

seisms of a different character than those presented here. However, Bath(9) concludes that the microseisms recorded at Uppsala, Sweden, apparently of the type discussed here, and to be further discussed in Part II, are probably a result of surf on the nearest Norwegian coast.

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